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Reservoir Fluids Evaluation of Cretaceous Succession in the Bijeel-7 Well, Aqra Area, Iraqi-Kurdistan Region: Revealed by Gas Chromatography Logs Data

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ABSTRACT

This study evaluates the hydrocarbon potential of the Cretaceous succession in the Bijeel-7 (Sharafuna-1) Well, located in the Aqra area of Iraqi Kurdistan, through gas chromatographic analysis of hydrocarbons (C_1–C_5). The analysis focused on calculating key ratios for wetness (Wh), balance (Bh), and character (Ch) to identify hydrocarbon phases within the Shiranish, Aqra, Bekhme, Qamchuqa, Sarmord, and Chia Gara formations. The results revealed that the Shiranish Formation predominantly contains residual oil in its upper intervals and oil in its lower sections. The Aqra and Bekhme formations exhibited a mix of residual oil and oil-dominated intervals, with occasional gas or gas/oil phases identified in specific depths of the Bekhme Formation. The Qamchuqa Formation is primarily residual oil-dominated, with a transition to dry gas observed in its lower intervals. The Sarmord and Chia Gara formations showed a mixture of residual oil and oil phases, with a clear shift to oil dominance in their deeper sections. These findings provide valuable insights into the hydrocarbon potential and phase distributions across the studied formations, contributing to a better understanding of the petroleum system in the region. The present investigation can offer preliminary indications regarding the existence of hydrocarbons. This lowers the possibility of drilling dry Wells and aids in locating possible productive zones.

Evaluación de fluidos de reservorio en la sucesión cretácica del pozo Bijeel-7, área de Aqra, región del Kurdistán iraquí, a través de datos de registros cromatográficos de gases

RESUMEN

Este estudio evalúa el potencial de hidrocarburos de la sucesión Cretácica en el pozo Bijeel-7 (Sharafuna-1), ubicado en la zona de Aqra, Kurdistán iraquí, mediante análisis cromatográfico de gases de hidrocarburos (C_1–C_5). El análisis se centró en el cálculo de relaciones clave de humedad (Wh), balance (Bh) y carácter (Ch) para identificar las fases de hidrocarburos dentro de las formaciones Shiranish, Aqra, Bekhme, Qamchuqa, Sarmord y Chia Gara. Los resultados revelaron que la Formación Shiranish contiene predominantemente aceite residual en sus intervalos superiores y aceite en sus secciones inferiores. Las formaciones Aqra y Bekhme mostraron una mezcla de intervalos dominados por aceite residual y aceite, con fases ocasionales de gas o gas/aceite identificadas en ciertas profundidades de la Formación Bekhme. La Formación Qamchuqa está principalmente dominada por aceite residual, con una transición hacia gas seco observada en sus intervalos inferiores. Las formaciones Sarmord y Chia Gara presentaron una mezcla de fases de aceite residual y aceite, con un claro cambio hacia el dominio del aceite en sus secciones más profundas. Estos hallazgos proporcionan información valiosa sobre el potencial de hidrocarburos y la distribución de fases en las formaciones estudiadas, contribuyendo a una mejor comprensión del sistema petrolero en la región. La presente investigación puede ofrecer indicaciones preliminares respecto a la existencia de hidrocarburos, lo que reduce la posibilidad de perforar pozos secos y ayuda en la localización de posibles zonas productivas.

1. Introduction

The Akri-Bijeel Block is one among 55 blocks designated for oil exploration in the Kurdistan network Region in the northern part of Iraq. The Bijeel-7 (also known as Sharafuna-1) Well was drilled as an initial exploration Well and marks the seventh Well being drilled in the Akri-Bijeel Block. The sedimentary sequence from 3772 to 3806 m in this Well has been evaluated geochemically by Abdula (2017). He found that total organic carbon ranges between 0.50 and 4,31 wt.% and hydrogen index ranges between 129 and 216. The Well is located 20 km northeast of the Bijeel-1 Discovery Well, where the operator estimates a substantial 2.4 billion barrels of oil on the site. The interval between 1851 and 4270 from Bijeel-1 Well is investigated geochemically by Abdula et al. (2017). They recorded maximum TOC (7.78) with HI of 676m in Tertiary interval., The petroleum system of the Akri-Bijeel oil field shows that the Paleogene formations such as the Kolosh Formation seem to be immature. However, the Jurassic–Lower Cretaceous source rocks such as the Chia Gara, Naokelekan, and Sargelu formations are thermally mature and within the main oil window. The Triassic Kurra Chine and Geli Khana formations are thought to be in the high maturity stage and within the wet and dry gas windows, whereas the older formations are either within the dry gas zone or completely generated hydrocarbon stage and depleted after the hydrocarbons were expelled with subsequent migration to the reservoir rock of the structural traps (Abdula et al., 2020; Edilbi et al., 2025). The Akri-Bijeel Block encompasses an area of 889 km² (Csontos et al., 2012). Many Geological studies were already made with the logging data but few combined quick-look and chromatographic gas ratio analyses to evaluate a geological formation. Kandel et al. (2001) point out, gas analysis performed during drilling is actually essential to determining the reservoir's quality and characterizing its overall productivity of the Wellbore. Essential information for determining the hydrocarbon concentration is provided by drill fluid gas shows. By observing these gas displays, one can determine the Wellbore's potential output. During drilling operations, gas analysis aids in ensuring Well stability, Well control, and pore pressure comprehension. Reservoirs typically exhibit distinct geochemical signatures related to the types and quantities of hydrocarbons present. High-quality gas data is useful in detecting these indicators, which are necessary for assessing and characterizing reservoirs. Hydrocarbon connections like the Gas-Oil Contact (GOC) and the Oil-Water Contact (OWC) can be found with the aid of gas shows. Gas analysis contributes to our understanding of the contents for geological formations encountered during drilling operations, therefore helps with reservoir appraisal., Gas show monitoring during drilling operations is a valuable tool that Well site geologists can utilize for a number of objectives, including identifying the characteristics and hydrocarbon potential of the reservoir and guaranteeing the stability of the Wellbore. Thorough investigation and the utilization of certain ratios aid in refining the gathered data, which facilitates the making of Well-informed planning and evaluation decisions (Dashti et al., 2015). The purpose of gas chromatography is to identify and determine the relative quantity of each component by analyzing each hydrocarbon accumulation (Helander, 1983).

Accurate determination of the mud gas sample's composition is made possible using gas chromatography. Knowledge of the gas's composition enables the connection between methane and the heavier hydrocarbons to be established (Pixler, 1969). The Well-site geologist can quickly identify zones of interest that require more testing by using ratio calculations from mud gas data (Haworth et al., 1985). Two crucial ratios, the wetness ratio (Wh) and the balancing ratio (Bh), exhibit notable variations in behavior based on the gas density and hydrocarbon composition. As gas density increases, the wetness ratio (Wh) shows an increasing trend. This suggests that the percentage of heavy gas components is increasing in comparison to lighter gases (Haworth et al., 1985).

The balancing ratio (Bh) can be used to compare light and heavy hydrocarbons directly. It is used in conjunction with the wetness ratio for interpretive purposes. Because the balancing ratio is inversely related to the wetness ratio, it drops as fluid density increases. The ratio is employed to calculate or verify gas production potentials. For example, the balance ratio value will be very high when dry methane is present. However, it rapidly declines if there is any hint of heavy hydrocarbons linked to a profitable source (Haworth et al., 1985). The main aims of this article are to evaluate the hydrocarbon potential of the Cretaceous succession in the Bijeel-7 Well located in the Aqra

area of Iraqi Kurdistan using gas chromatographic analysis of hydrocarbons (C1–C5) extracted from mud log data. The study seeks to calculate three key geochemical ratios including (wetness (Wh), balance (Bh), and character (Ch)) to identify and classify different hydrocarbon phases (residual oil, oil, gas, gas/oil mixtures, and condensate) within six Cretaceous formations (Shiranish, Aqra, Bekhme, Qamchuqa, Sarmord, and Chia Gara).

2. Regional Geological Setting of the Study Area

The Aqra area is located in Iraqi Kurdistan and falls within the broader geological and tectonic setting. The Aqra area is situated within the northern segment of the Western Zagros Fold-Thrust Belt, which extends from southeastern Turkey through northern Iraq and western Iran. This belt represents the deformational zone resulting from the collision between the Arabian Plate and the Eurasian Plate.

The tectonic activity in the Aqra area is characterized by ongoing compression and folding due to the convergence of the Arabian and Eurasian Plates. The collision has resulted in the formation of large-scale anticlines, synclines, and thrust faults within the North Western Zagros Fold-Thrust Belt (Motiei, 1993). These structures are responsible for the development of significant oil and gas traps in the region (Alavi, 2004). The Bijeel-7 Well, located in the Aqra area of Iraqi Kurdistan, is situated within the larger geological setting of the Western Zagros Fold-Thrust Belt.

It is important to note that a comprehensive understanding of the regional geological setting of the Bijeel-7 Well would require access to detailed geological studies, Well reports, and subsurface data specific to these Wells (Buday, 1980). These sources would provide more precise information about the lithology, structural characteristics, and hydrocarbon potential of the formations encountered in the Wells within the Aqra area of Iraqi Kurdistan. The stratigraphy of the region consists of sedimentary rocks that were deposited during the Mesozoic and Cenozoic eras. The formations encountered in the Bijeel-7 Well, as mentioned in the previous response, represent different geological units within this stratigraphic sequence. These formations, ranging from the Late Triassic to the Late Cretaceous, comprise various lithologies such as sandstone, shale, limestone, and anhydrite. They were deposited in different environments, including marine, deltaic, and fluvial systems, reflecting the changing geological conditions over time (Buday and Jassim, 1987).

In the northern region of Iraqi Kurdistan, the Akre area is a mountainous region with a rugged topography. It is situated in the High Folded Zone and is roughly Long. 43° 37 35.7 E to 44°18 12.7 E in the west and Lat. 36° 31 54.0 to 36° 53 15.9 N, and Long. 43° 37 35.7 E to 43° 53 15.9 E in the west and Lat. 36° 43 52 N to 36° 53 15.9 N. It is estimated that the district spans an area of around 1,600 km2. The district center of Akre is situated 118 km north-west of Erbil City. The eastern and western regions of the territory are naturally bordered by the Khazir and Greater Zab rivers, respectively (Asaad and Balaky, 2021). The Bijeel-7 Well, is situated in the elevated terrain of the southern region within the Akri-Bijeel Block in northern Iraq. Specifically, it is located approximately 12 km northwest of the city of Harir and 50 km north of the regional capital city, Erbil. Its precise geographical coordinates are latitude 36° 38' 40.8" North and longitude 44° 9' 28.3" East, as depicted in (Fig. 1).

3. Materials and Methods

The mud logs were carefully examined, and specific gas peaks found within the reservoir sections were chosen for additional analysis. The gas chromatographic data, covering compounds C_1 to C_5. Subsequently, calculations were performed to determine their wetness, character, and balance ratios. These ratios were computed using the formulas outlined by Harworth et al. (1984) and Harworth et al. (1985) (Table 1 and 2).

The gas chromatographic data that represents the concentrations of (C_1 to C_5) in ppm, were categorized as following: (Haworth et al., 1985; Pierson 2017):

C_1: Methane (CH_4), C_2: Ethane (C_2H_6), C_3: Propane (C_3H_8), iC_4: Isobutane (C_4H_{10}), nC_4:

Normal butane (C_4H_{10}), iC_5: Isopentane (C_5H_{12}), nC_5: Normal pentane (C_5H_{12}).
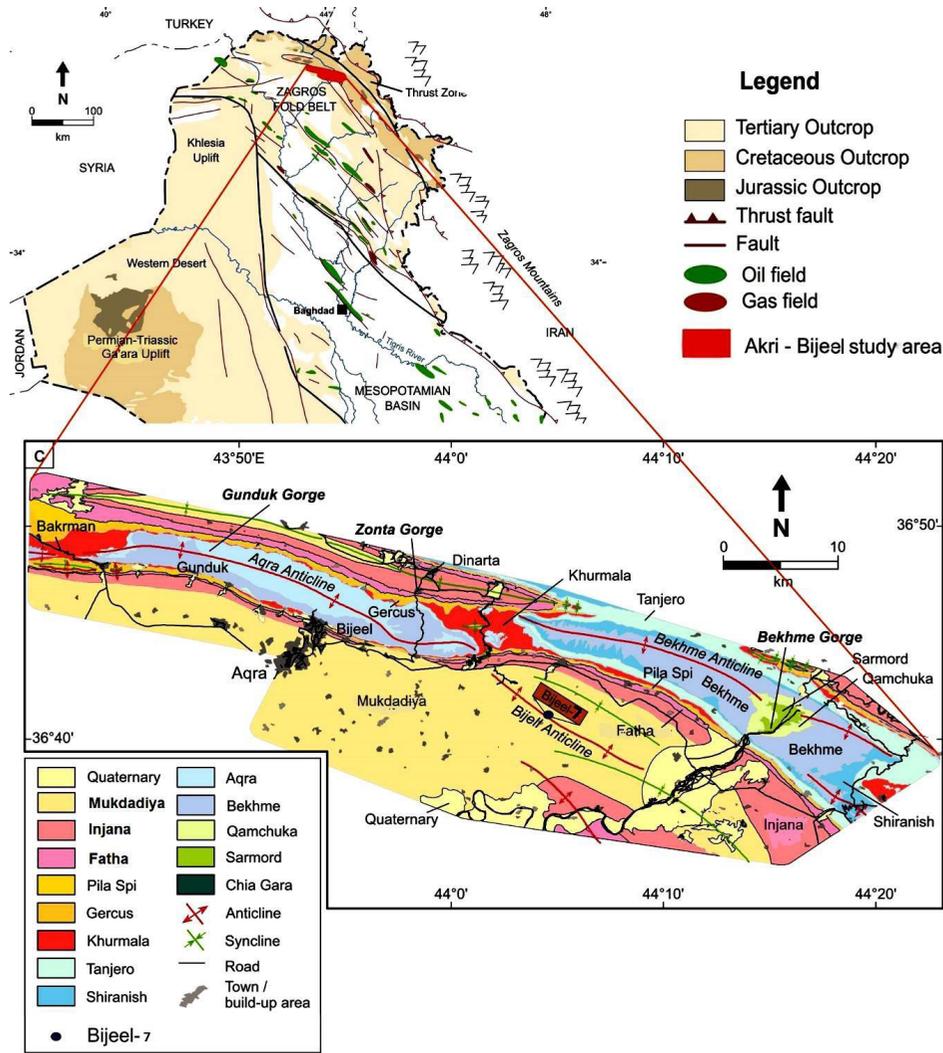
Figure 1. The upper part of the image shows the primary map of oil and gas reserves in the area, the examined Well's location, and the folded Zagros belt. The lower part of the image is a geological map of the region that shows the two main anticlines (Modified from Abdula et al., 2017; Pitman et al., 2004; Csontos et al., 2012).

1. **Wetness (Wh) liquid portion of C_1-C_5 alkanes:** The geochemical parameter is used to quantitatively express the ratios of components in relation to C_1. These ratios are determined using the following calculations (Haworth et al., 1985; Hawker, 1999; Pierson, 2017):

$$Wh = \frac{C_2 + C_3 + iC_4 + nC_4 + iC_5 + nC_5}{c_1 + c_2 + c_3 + iC_4 + nC_4 + iC_5 + nC_5} * 100 \qquad (1)$$

2. **Balance (Bh):** The geochemical parameter represents the correlation between the lighter and heavier components. A high Bh value indicates the dominance of hydrocarbon gas (HC), while a low value suggests that the heavier components (oil) should be considered in conjunction with Wh. There is a negative correlation between the wetness ratio and the balance ratio; that is, the balance ratio decreases as fluid density increases (Mode et al., 2014). The proximity between these values and the crossover point signifies the transition from lighter hydrocarbon gas (including gas precipitation) to the heavier oil components (Hawker, 1999; Haworth et al., 1985; Pierson, 2017):

$$BH = \frac{C_1 + C_2}{C_3 + iC_4 + nC_4 + iC_5 + nC_5} \qquad (2)$$

3. **Character (Ch) compares C_3-C_5 Alkanes (wet gas-oil phase):** In the case where Wh is greater than 0.5, it indicates the presence of a wet or condensate hydrocarbon. On the other hand, if Wh falls between 0.5 and 17.5, and Bh, Wh, and Ch are all greater than 0.5, it suggests the presence of an oil reservoir with high API density and/or high gas-to-oil ratio (GOR) (Hawker, 1999; Haworth et al., 1985; Pierson, 2017).

$$Ch = \frac{iC_4 + nC_4 + iC_5 + nC_5}{C_3} \qquad (3)$$

As previously stated, these interpretations are based on numerous empirical observations (Haworth et al., 1985).

The Ch ratio was chosen to interpret shows where, in certain circumstances, high methane readings indicated a lighter hydrocarbon fluid character, using only Wh and Bh, than was actually present in the reservoir. These situations were associated with gas-cap, dual oil/gas, and water-wet zones (Haworth et al., 1985):

4. **BAR2 (Baroid, C_1/C_2):** This empirical parameter serves as a tool for interpreting the origin of hydrocarbons (HC). In addition to interpreting Wh and Bh values, it can also provide indications of productive or wet zones (Haworth et al., 1985; Pierson 2017).

The (Pixler,1969) was mention to the hydrocarbon ratio plots and nonproductive reservoirs from the ratio of C_1/C_2 (BAR2) as If BAR2 <2

nonproductive zone, If 2 < BAR2 < 10 gas coming from oil reservoir, while If 10 < BAR2 < 35 gas coming from gas reservoir and If 35 < BAR2 gas in contact with water nonproductive.

According to Hawker (1999) and Pierson (2017), the ideal ratio correlations to the reservoir fluid type depicted in Table 3,4, and 5 are as follows:

A. **Very light gas:** The deposit releases mostly methane gas, with trace amounts of ethane as Well. The Bh ratio does not fall below 100, the set point for extremely dry gas, while the Wh ratio rises. According to Haworth et al. (1985), the Ch ratio is zero, indicating the absence of the heavier hydrocarbon gases.

B. **Medium-density gas:** In this case, the Wh ratio indicates gas since it is larger than 0.5 but less than 17.5. This theory is supported by the Bh ratio's position, which points to a medium-density gas. Because Ch is smaller than 0.5, the Ch ratio confirms the interpretation of the gas (Haworth et al., 1985).

C. **Gas/oil zone:** As previously mentioned, methane levels in this case cause the Wh and Bh ratios to indicate gas. However, since the Ch value is higher than 0.5, it can be concluded that gas and oil are associated (Haworth et al., 1985).

D. **Coal horizon:** In this case, coal gas—which is primarily composed of ethane and methane-produces a false Wh value that suggests the presence of oil. However, both Bh and Ch indicate dry gas. The existence of coal is confirmed by lithological observation (Haworth et al., 1985).

E. **Medium-gravity oil:** The relationship between the curves seen throughout the investigation when entering a medium-gravity oil zone is depicted in this graphic. The density of the oil is indicated by the location of the Bh ratio, which is between 17.5 and 40 in the Wh ratio (Haworth et al., 1985).

F. **Residual oil:** The plot illustrates that Wh is larger than 40 and Bh is significantly smaller than Wh. In our investigation, this phenomenon was linked to the presence of tar and asphaltenes. In this case, the methane concentration is below 60%, indicating a low proportion of volatile substances and a likely absence of mobility. These phenomena may also be linked to low total gas readings (Haworth et al., 1985).

In other words, the contact is not a sudden boundary, but rather an area where the water content gradually increases. The curves exhibit a noticeable shift in character, suggesting a decrease in the density of pore fluids, followed by an increase in density, and then irregular movement due to variations in gas concentration and permeability (Haworth et al., 1985).

Table 1. Hydrocarbon Types with ratios level (Haworth et al., 1985).

Hydrocarbon Type	C1/C2 Ratio	C1/C3 Ratio	C1/C4 Ratio	C1/C5 Ratio	Wh (Wet Hydrocarbons)	Bh (Butanes & Heavier)
Dry Gas	High (>10)	High (>5)	Very High	Very High	Low	Low
Wet Gas	Moderate (<10)	Moderate	Moderate	Lower	Higher	Moderate
Oil	Low	Low	Low	Low	High	High
Residual Oil	Low	Low	Low	Low	Very High	Very High

Table 2. Summary of Fluid Interpretation with Wh, Bh, and Ch Ratios (Haworth et al., 1985).

Wh Ratio	Fluid Type	Bh Ratio	Ch Ratio
< 0.5	Very Dry Gas	Bh > 100 (Very dry gas)	Ch < 0.5
0.5 - 17.5	Gas	Bh> Wh (Gas, with density rising)	Ch < 0.5
17.5 - 40	Oil	Bh <Wh (Gas/oil or gas/condensate)	Ch< 0.5 or Ch > 0.5
> 40	Residual Oil	Bh << Wh (Residual Oil)	Ch> 0.5 (Oil-associated gas)

Lithological Description of the study formations

The provided lithological description indicates the different formations and their lithologic composition during Cretaceous in the Bijeel-7 Well from Aqra, Iraqi Kurdistan Regions. Here is a summary and analysis of the lithology for each formation (Fig. 2):

Shiranish Formation-Late Cretaceous- (2424-2545m):

It was defined from the High Folded Zone of Northern Iraq near the village of Shiranish Islam, NE of Zakho. The Shiranish Formation, in its type area, comprises thin bedded argillaceous limestones (locally dolomitic) overlain by blue pelagic marls (Buday and Jassim, 1987). Limestone conglomerates (probably resulting from slumping) occur locally in the formation in the Sinjar area of NW Iraq and in the Jabal Abdul Aziz area of Syria (AL-Mutwali and AL-Juboury, 2005). The formation gradually passes into the Tanjero Formation to the NE. Fossils are very abundant in the Shiranish Formation and its Qurna tongue but rare in the Jib'ab facies (Buday and Jassim, 1987). Abdula et al. (2018) confirm the formation's late Campanian-Maastrichtian age. The Shiranish Formation in the studied section primarily composed of limestone with a thickness of 121 meters. The uppermost part also contains marl and claystone layers. According to evidence presented by Al-Mutwali et al. (2025), Danian sequences exist in Iraq and can be the Duhok Dam considered the most perfect Shiranish and Kolosh Formations (Cretaceous-Paleogene) boundary sections in the country to date.

Aqra Formation-Late Cretaceous (2545-2688m):

It was defined from the Aqra anticline of the High Folded Zone of N Iraq as a reef limestone complex with massive rudist, shoal facies, and detrital forereef limestone. It is locally dolomitized, siliceous, and impregnated with bitumen (Buday and Jassim, 1987). From the studied section this formation has a thickness of 143 meters and is mainly composed of limestone, with a few marl strings throughout.

Bekhme Formation-Late Cretaceous (2688-2905m):

It was defined from the Bekhme Gorge of the Greater Zab River in the High Folded Zone as bituminous secondary dolomite, replacing organic detrital limestones in its upper part, and reef detrital limestones, alternating with basal breccia conglomerate in the lower part. It is difficult to separate the two formations where an intervening tongue of the Shiranish or Tanjero formations is absent (Buday and Jassim, 1987; Karim et al., 2022). The name Aqra-Bekhme has been suggested by Buday (1980) where these intervening formations are absent. The formations were deposited mostly in a reef-forereef environment (Buday and Jassim, 1987). From the studied section the Bekhme Formation is characterized by dolomitic limestone with interbedded limestone layers in the upper part. The middle and lower parts consist of calcareous dolomite.

Qamchuqa Formation-Late Cretaceous (2905-3095m):

The Qamchuqa Formation is a heterogeneous group of limestones. The lower part consists of Well bedded black limestones with chert nodules that intercalated with very thin black marly layers rich in organic matter, these limestones are most possible belonged to Aptian to Albian age, the lower part of the Qamchuqa Formation is not developed everywhere. Very often the thickly bedded partly reefal limestones of the upper part are overlying directly the marls of the Sarmord Formation. This might indicate the existence of horst-graben structures at Early Cretaceous time (Buday and Jassim, 1987). From the studied section this formation has a thickness of 190 meters and is lithologically described as calcareous dolomite with interbedded limestone and claystone layers in the upper part. The middle and lower parts consist of limestone with traces of claystone, and below 3070m, siltstone strings are present. Its upper boundary can be recognized by thin layers of shale rich in glauconite (Nourmohamadi et al., 2020).

Sarmord Formation-Early Cretaceous (3095-3390m):

The Sarmord Formation was defined in the Surdash Anticline of the High Folded Zone in the Sulaimaniya area of NE Iraq and the formation was

deposited in a deep inner shelf to outer shelf environment. The formation contains a higher proportion of limestones towards the SW where it passes laterally into the Qamchuqa Formation (Buday and Jassim, 1987). It comprises 455 m of homogeneous brown and bluish marls, with beds of argillaceous limestones and is dated as Valanginian-Aptian (Al-Abbasi1, Al-Mutwali and Al-Banna, 2021). From the studied section with a thickness of 295 meters, this formation is primarily composed of limestone. The upper part also contains marl and siltstone strings, while the lower part consists of silty marl interbedded with limestone layers and streaks.

Chia Gara Formation-Early Cretaceous (3390-3682m):

Throughout the outcrop area the formation comprises up to 230 m of thin bedded limestone and calcareous shale, with a consistent phacoid bed at the base (Edilbi and Sherwani, 2019). In the Northern Thrust Zone, the uppermost beds of the formation are silty. In Well Kirkuk-109 conglomeratic beds occur at the base of the formation (Al-Abbasi, Al-Mutwali and Al-Banna, 2018). The Chia Gara Formation (along with the Karimia Formation) is generally restricted to the Unstable Shelf. In the Foothill Zone the formation gradually passes into the Makhul Formation SW of the Butmah-Chemchemal Subzone, and is absent west of the Tigris River (Buday and Jassim, 1987; Abdula, 2010; Abdula et al., 2015). From the studied section this formation has a thickness of 292 meters. It is lithologically described as calcareous marl with silty limestone streaks and limestone beds in the upper part. The middle part consists of calcareous siltstone with silty marl, and the lower part is composed of calcareous marl alternating with silty marl layers and calcareous siltstone strings. The formation is rich in organic matter as the range of total carbon content (TOC) is between 0.84 and 2.87% and with an average of 1.56 wt.% (Abdula et al., 2021).

Figure 2. Generalized stratigraphic column of the Bijeel-7 from Aqra- Iraqi Kurdistan Region.

4. Results and Discussion

The hydrocarbon characterization across different intervals from the youngest to older formations of the studied formations reveals a complex interplay between gas and oil phases, transitioning between dry gas, gas-condensate, and oil zones. To provide a comprehensive analysis at every 20-meter interval, it will break down the data into different sections based on the available depth values from each formation. This will involve interpreting the gas chromatographic data (C_1 to C_5 hydrocarbons), wetness ratio (Wh), balance ratio (Bh), and character ratio (Ch) for each interval, in addition to C_1/C_3, C_1/C_4, and C_1/C_2 ratios.

Wh and Bh serve as complementary data for identifying whether the hydrocarbon represents gas or oil, and they assist in assessing the density and phase of the fluid. By plotting Wh and Bh, researchers can interpret gas, oil, and residual oil zones and successfully identify gas/oil mixtures or gas condensate systems. The Ch ratio offers additional support by indicating whether the hydrocarbon fluid contains a higher concentration of methane, which could suggest gas-cap or dual-phase oil/gas zones.

To analyze specific zones and depths from the mud log information for various depths, detailing the concentrations of hydrocarbons (C_1 to C_5), their ratios (C_1/C_2, C_1/C_3, C_1/C_4), and additional parameters like Wh, Bh, and Ch. The values for Wh (Wetness Ratio), Bh (Balancing Ratio), Ch (Character ratio) and C_1/C_2 ratio allow for the classification and interpretation of fluid types (gas, oil, residual oil, etc.). The current research focuses on specific zones based on depth and interpret the fluid types and behavior according to the provided ratios and fluid properties. Below is an analysis of the data based on the trends observed in the ratios (Table 3, 4, and 5).

The present study investigates the hydrocarbon potential of the Cretaceous successions in the Bijeel-7 Well, located in the Aqra area of Iraqi Kurdistan. Gas chromatographic analysis of hydrocarbons (C_1–C_5) was conducted to calculate key ratios: wetness (Wh), balance (Bh), and character (Ch), which were used to identify and evaluate hydrocarbon phases across the Shiranish, Aqra, Bekhme, Qamchuqa, Sarmord, and Chia Gara formations.

Table 3. Formation Hydrocarbon Phase Distribution and Diagnostic Ratios.

Formation	Depth Range (m)	Dominant Hydrocarbon Phase	Wh Range	Bh vs Wh Relationship	C1/C4 vs C1/C3	C1/C2 Range	Key Observations
Shiranish	2430-2500	Residual Oil	Wh > 40	Wh > Bh	C1/C4 > C1/C3	< 15	Upper zone dominated by residual oil
Shiranish	2505-2545	Oil	17.5 < Wh < 40	Wh > Bh	C1/C4 > C1/C3	< 15	Lower zone shows oil dominance
Aqra	2550-2688	Residual Oil & Oil (Mixed)	Wh > 40 (upper) 17.5 < Wh < 40 (lower)	Wh > Bh	C1/C4 > C1/C3	< 15	Mixed intervals of residual oil and oil
Bekhme	2690-2900	Residual Oil, Oil & Gas (Mixed)	Wh > 40 (middle/lower) 17.5 < Wh < 40 (middle) 0.5 < Wh < 17.5 (at 2760m, 2775m)	Wh > Bh (oil zones) Bh > Wh (gas zones)	Variable	C1/C2 = 5-6.927 C1/C3 = 7-67.647	Gas identified at 2760m and 2775m; gas/oil or gas/condensate at 2775m; mixed hydrocarbon reservoir
Qamchuqa	2905-3095	Residual Oil with Dry Gas Transition	Wh > 40 (most intervals) 0.5 < Wh < 17.5 (3085-3090m)	Wh > Bh (residual oil) Bh > Wh (dry gas)	C1/C4 > C1/C3	< 15 (oil zones) >> 15 (gas zones at 3085-3090m)	Transition to dry gas between 3085m and 3090m
Sarmord	3100-3385	Residual Oil & Oil	Wh > 40 (most intervals) 17.5 < Wh < 40 (deeper)	Wh > Bh	C1/C4 > C1/C3	< 15	Shallow depths (3100-3200m) show oil zones; middle part (3200-3348m) shows mixed residual and oil zones
Chia Gara	3390-3660	Residual Oil & Oil	Wh > 40 (upper) 17.5 < Wh < 40 (deeper)	Wh > Bh	C1/C4 < C1/C3	< 15	Combination of residual oil and oil phases

Table 4. Hydrocarbon Phase Interpretation Criteria.

Parameter	Residual Oil	Oil	Gas	Gas/Oil or Gas/Condensate
Wh (Wetness Ratio)	Wh > 40	17.5 < Wh < 40	0.5 < Wh < 17.5	Variable
Wh vs Bh	Wh > Bh	Wh > Bh	Bh > Wh	Transitional
C1/C4 > C1/C3	C1/C4 > C1/C3	C1/C4 vs C1/C3	Variable	Variable
C1/C2	< 15	< 15	> 15	Variable

Table 5. Gas-Prone Intervals Identified.

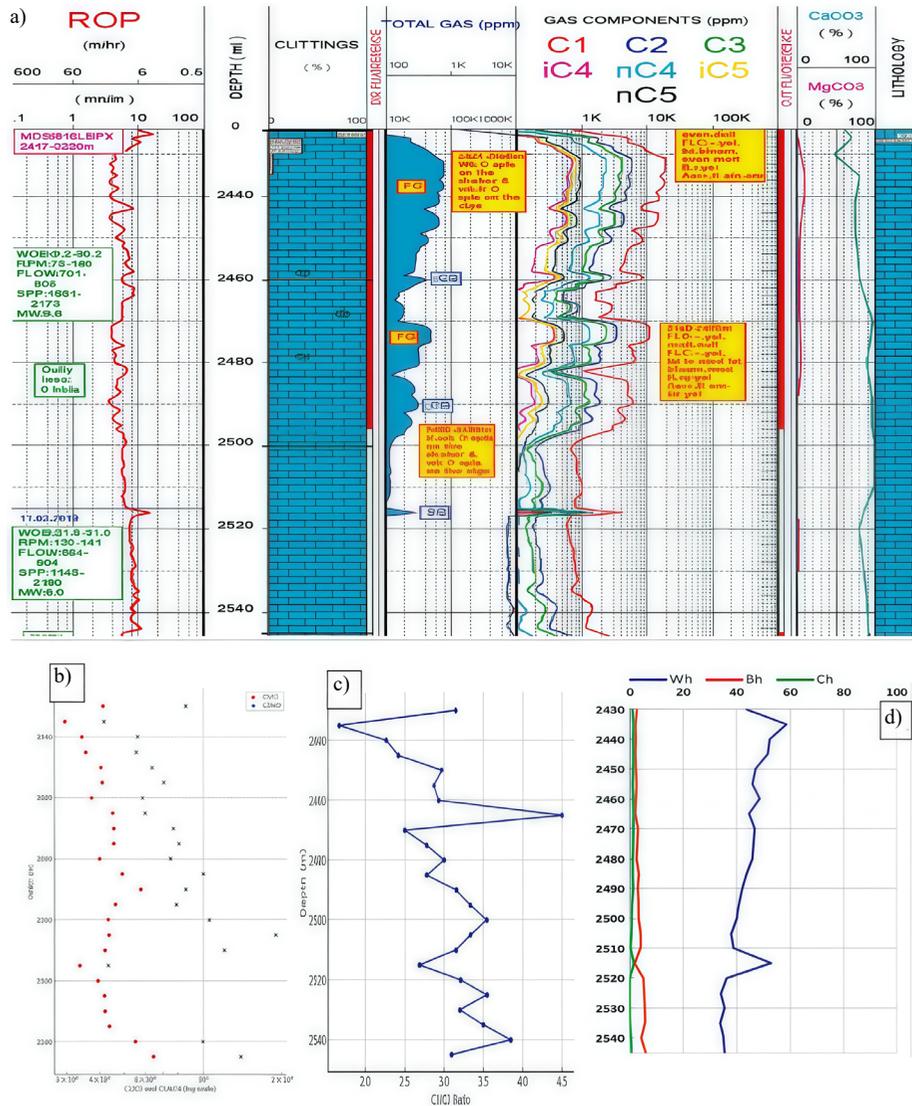| Depth Interval (m)	Formation	Hydrocarbon Type	Wh Range	Key Ratios
2760	Bekhme	Gas	0.5 < Wh < 17.5	Bh > Wh
2775	Bekhme	Gas/Oil or Gas/Condensate	Variable	Oil density increases with Wh
3085-3090	Qamchuqa	Dry Gas	0.5 < Wh < 17.5	Bh > Wh; C1/C2 > 15

Figure 3. (a) ROP, Gas Composition, and Lithology Log for the Shiranish Formation. (b, c, and d) Mud gas diagnostic ratio log for the Shiranish Formation. The diagnostic ratios defined by Haworth et al. (1985), C_1/C_2, C_1/C_3 and C_1/nC_4 Vs Depth, WHR (wetness ratio), BHR (Balance ratio) and CHR (character ratio).

In the Shiranish Formation (2430 to 2545m), residual oil dominates the upper zone (2430 to 2500m), where Wh is consistently higher than Bh (Wh > 40), (C_1/C_4) exceeds (C_1/C_3), and (C_1/C_2) is below 15, indicating the presence of residual oil. The C_1/C_4 ratio is greater than the C_1/C_3 ratio in the oil and condensate zones (Reda et al, 2024, Farouk et al., 2024). The lower zone (2505m to 2545m) is oil-dominated, as Wh remains greater than Bh (17.5 < Wh < 40), with the same ratios confirming oil (Fig. 3 A, B, C and D). The Aqra Formation (2550m to 2688) shows a mix of residual oil and oil-dominated intervals. Residual oil is evident in intervals where Wh > 40, (C_1/C_4) exceeds (C_1/C_3), and (C_1/C_2) is below 15, while oil dominates in lower intervals where Wh ranges between 17.5 and 40 (Fig. 4 A, B, C, and D). The Bekhme Formation (2690m to 2900m) contains a mixture of residual oil, oil, and occasional gas. Residual oil dominates the middle and lower sections, with Wh > 40, while oil is prominent in specific middle intervals (17.5 < Wh < 40). The (2760m and 2775m) interval, gas is identified where Bh surpasses Wh (0.5 < Wh < 17.5), and at 2775 m, gas/oil or gas/condensate is observed, with oil density increasing alongside Wh. C_1/C_2 and C_1/C_3 show variability at different depths, with some very high ratios (e.g., Depth 2690: C_1/C_2 = 5, Depth 2730: C_1/C_2 = 6.927), which could indicate that C_1 is much larger relative to C_2 and C_3 at some depths. For C_1/C_3, the trends are relatively consistent at around 7, but with some deeper dips and increases (e.g., Depth 2720 has a ratio of 7.762, whereas

Depth 2765 has a ratio of 67.647). This suggests there may be substantial changes in the relationship between C_1 and C_3 at certain depths. iC_4 and nC_4 represent two distinct indices related to C_4 or another element/compound, with values differing significantly across depths. Based on the data, the depth profile seems to indicate a mixed hydrocarbon reservoir, with characteristics of both natural gas (at shallower depths with high C_1) and oil (at deeper depths, especially where C_4 and C_5 hydrocarbons are more abundant). The presence of higher alkanes like butane (C_4) and pentane (C_5) at certain depths, along with the variability in the ratios, suggests that oil, potentially residual oil, could be present at these depths (Fig. 5 A, B, C, and D). The Qamchuqa Formation (2905m to 3095m) is largely residual oil-dominated, with Wh > 40, (C_1/C_4 > C_1/C_3), and (C_1/C_2 < 15). However, a transition to dry gas occurs between 3085m and 3090m, where Bh exceeds Wh (0.5 < Wh < 17.5) and (C_1/C_2) exceeds 15. The data reveals variation in the ratios and values across the depths measured. Specifically, C_1 tends to be the largest parameter, and its relative magnitude (compared to C_2, C_3, etc.) changes as move deeper. The fluctuations in ratios and parameters could reflect geological, environmental, or other underlying factors at each depth. The changing ratios and the presence of C_5 compounds help in identifying where oil or residual might dominate (Fig. 6 A, B, and C). In the Sarmord Formation (3100m to 3385m), residual oil dominates most intervals (Wh > 40), but oil becomes prominent in deeper intervals

(17.5 < Wh < 40), with ($C_1/C_4 > C_1/C_3$) and ($C_1/C_2 < 15$) supporting these findings. Shallow depths (around 3100-3200 meters) generally show oil zones with average of Wh value is higher than 40. At the middle part of the formation (3200-3348 meters) show increasing in Wh and $C_1\backslash C_4$, in addition to lower values in $C_1\backslash C_2$. The C_1/C_2 and C_1/C_3 ratios are typically lower here, which might suggest mixed between residual and oil zones (Fig. 7 A, B, and C). Similarly, the Chia Gara Formation (3390m to 3660m) displays a combination of residual oil and oil phases. Residual oil is prevalent where Wh > 40, while oil dominates in deeper sections (17.5 < Wh < 40), with the ($C_1/C_4 < C_1/C_3$) ratios and ($C_1/C_2 < 15$) confirming the hydrocarbon phases. This comprehensive analysis provides insights into the hydrocarbon distribution and phase transitions across the formations in the Bijeel-7 Well (Fig. 8 A, B, and C).

Finally, from all formations C_1, C_2, C_3, C_4, and C_5 are positively correlated with Wh suggesting their increase correlates with higher quantities of oil and residual oil. C_1/C_2, C_1/C_3, C_1/C_4 ratios seem to indicate oil when the ratios are lower, and residual oil when they are lowest. Both Bh and Ch increase with Wh, indicating that these parameters are closely associated with residual oil zones.

Based on gas-to-liquid ratio suggests a potential for gas, the (Wh) values from 17.5 to 40 across all the intervals (except for a few depths that might fall below 17.5 Wh) indicate that the zones are predominantly oil-bearing. Only those few specific depths with Wh < 17.5 would potentially suggest gas. Based on this, none of the intervals from 2760m, 2775m and 3085m to 3090m seem to be optimal for gas extraction when considering the Wh. These intervals indicate oil or residual oil zones, with only some very specific depths potentially being gas bearing zone. The entire depth range from 2430m to 3660m appears to be primarily oil-bearing with no significant indications of gas. Oil is the dominant hydrocarbon in these intervals, and the presence of residual oil could be inferred in some of the deeper sections where Wh ratios approach or exceed 40.

The analysis and interpretation of gas chromatographic data across the Shiranish, Aqra, Bekhme, Qamchuqa, Sarmord, and Chia Gara Formations reveal diverse fluid characteristics and transitions, reflecting the geological complexity and hydrocarbon dynamics in these formations. Each formation exhibits distinct patterns of hydrocarbon composition, ranging from residual oil zones to oil-dominated regions with gas from some specific depth, which are influenced by depth and reservoir properties. These variations are critical for understanding the potential productivity and type of hydrocarbons present in each formation.
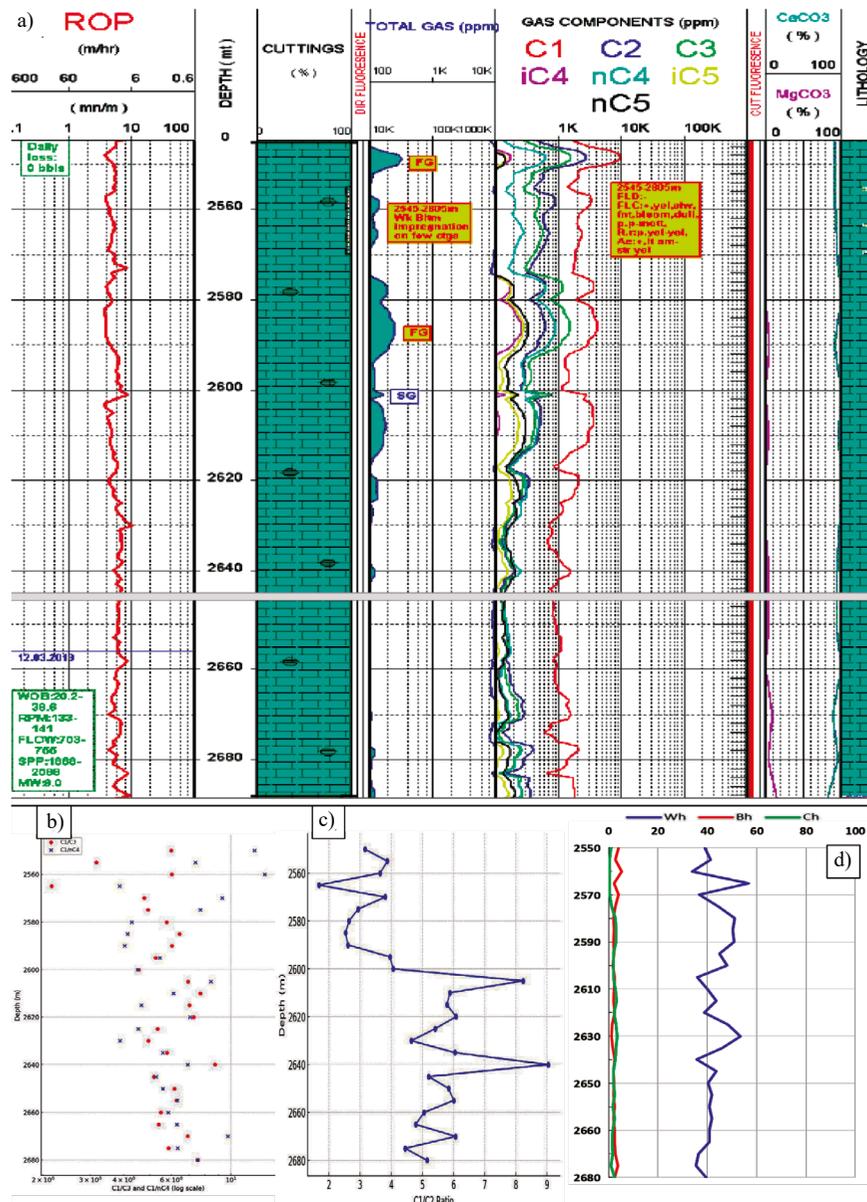

Figure 4. (a) ROP, Gas Composition, and Lithology Log for the Aqra Formation. (b, c, and d) Mud gas diagnostic ratio log for the Aqra Formation. The diagnostic ratios defined by Haworth et al. (1985), C_1/C_2, C_1/C_3 and C_1/nC_4 Vs Depth, WHR (wetness ratio), BHR (Balance ratio) and CHR (character ratio).
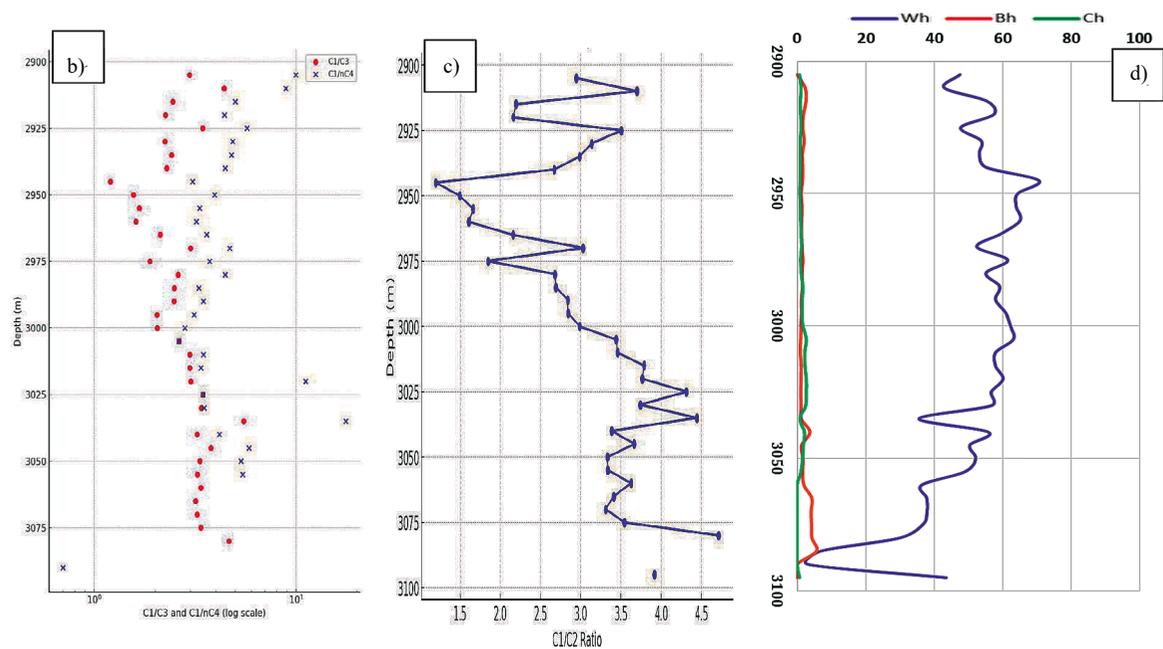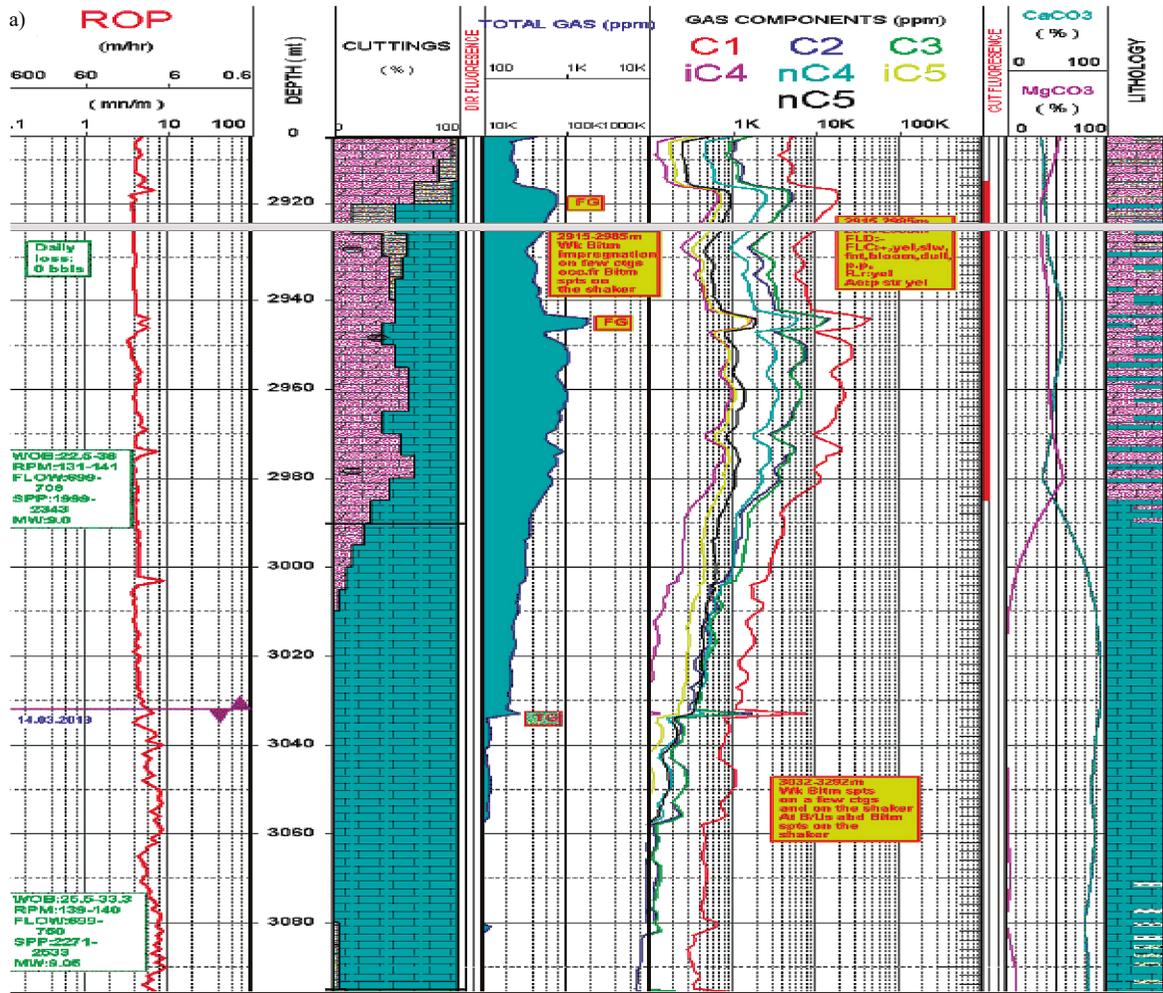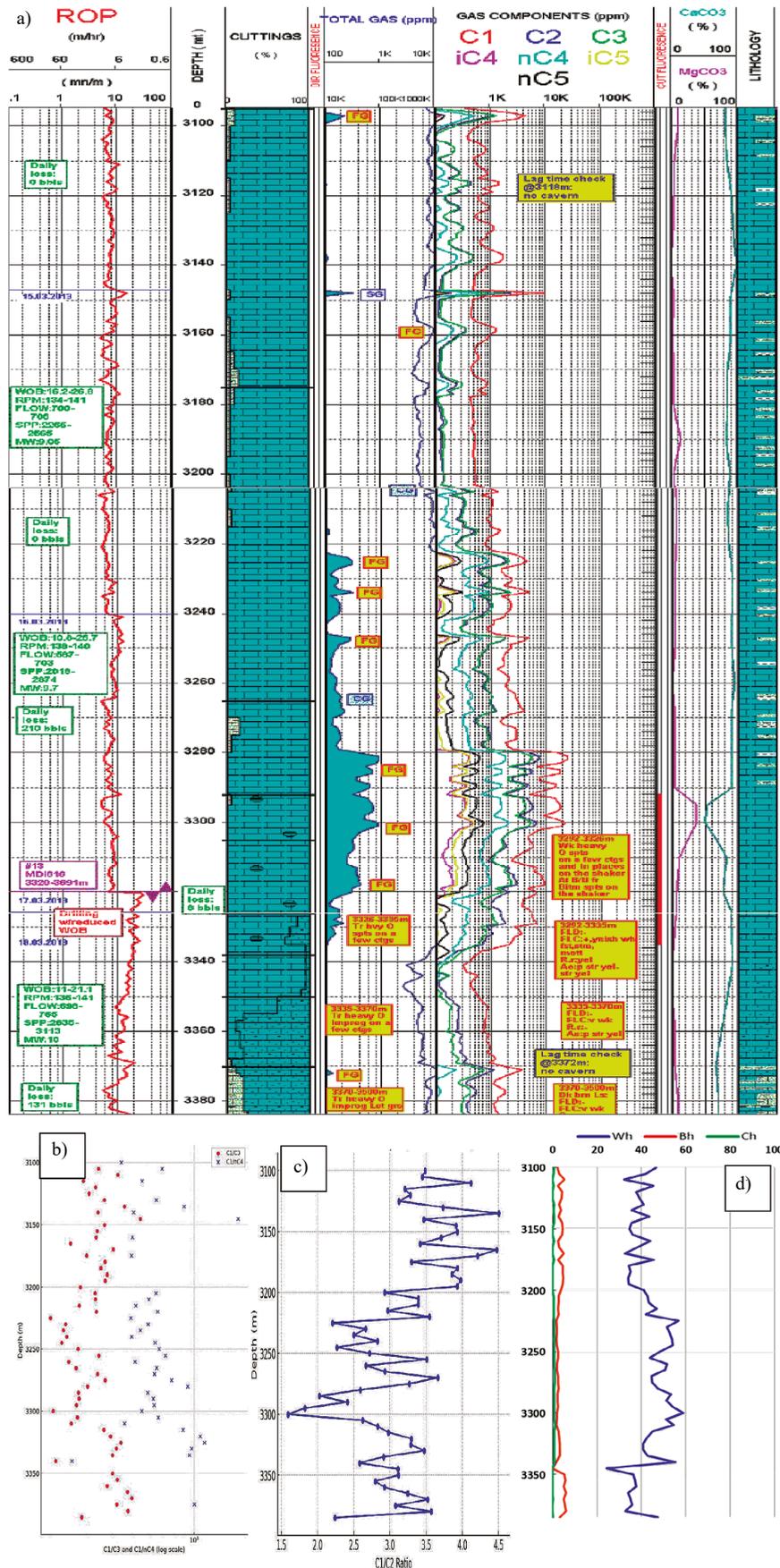
Figure 5. (a) ROP, Gas Composition, and Lithology Log for the Bekhme Formation. (b, c, and d) Mud gas diagnostic ratio log for the Bekhma Formation. The diagnostic ratios defined by Haworth et al. (1985), C_1/C_2, C_1/C_3 and C_1/nC_4 Vs Depth, WHR (wetness ratio), BHR (Balance ratio) and CHR (character ratio).

Figure 6. (a) ROP, Gas Composition, and Lithology Log for the Qamchuqa Formation. (b, c, and d) Mud gas diagnostic ratio log for the Qamchuqa Formation. The diagnostic ratios defined by Haworth et al. (1985), C_1/C_2, C_1/C_3 and C_1/nC_4 Vs Depth, WHR (wetness ratio), BHR (Balance ratio) and CHR (character ratio).
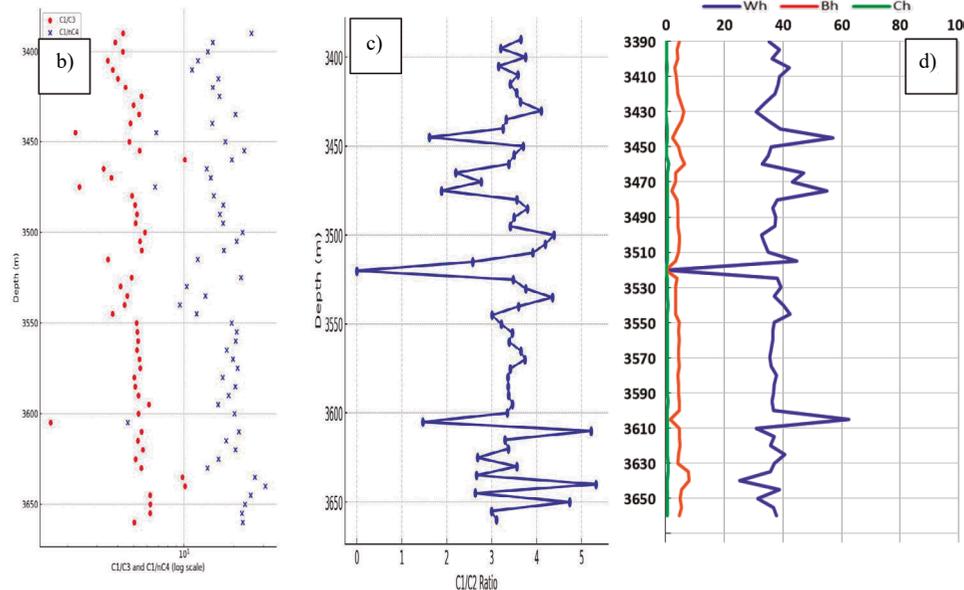
Figure 7. (a) ROP, Gas Composition, and Lithology Log for the Sarmord Formation. (b, c, and d) Mud gas diagnostic ratio log for the Sarmord Formation. The diagnostic ratios defined by Haworth et al. (1985), C_1/C_2, C_1/C_3 and C_1/nC_4 Vs Depth, WHR (wetness ratio), BHR (Balance ratio) and CHR (character ratio).
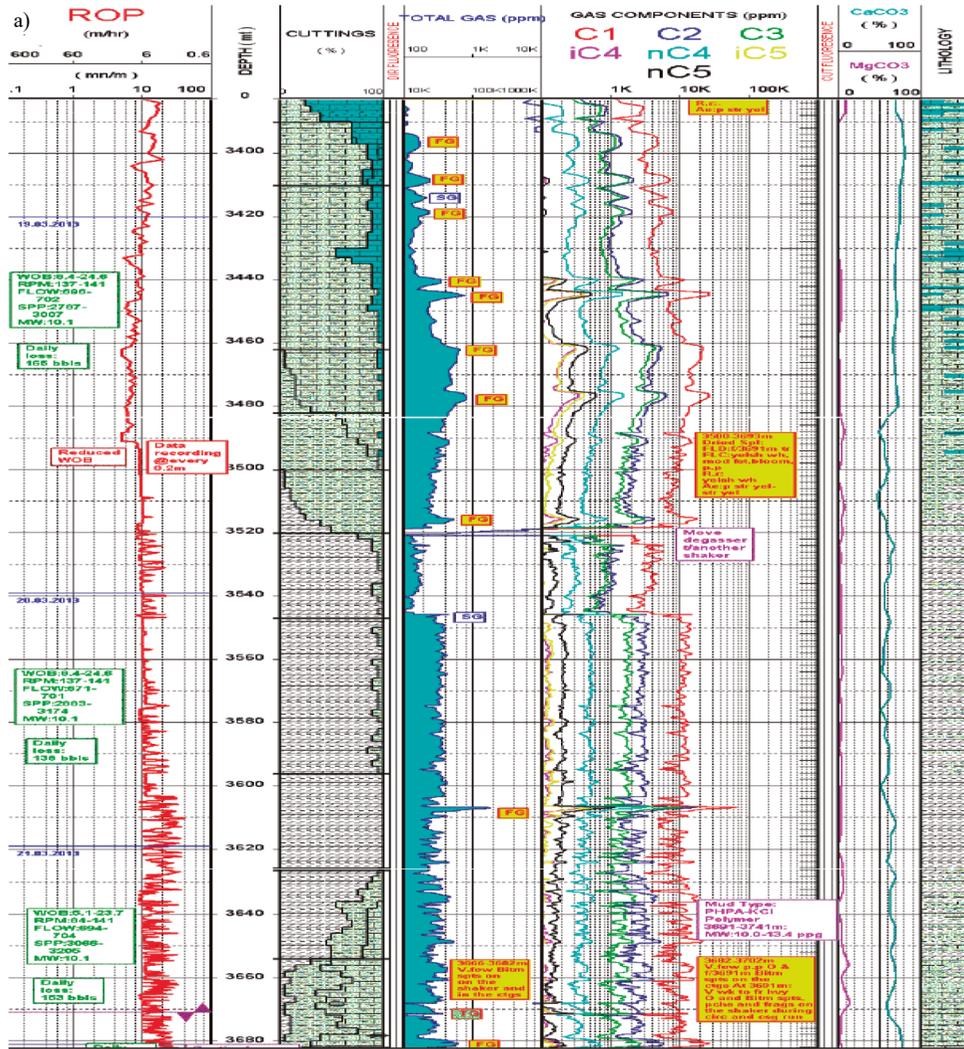
Figure 8. (a) ROP, Gas Composition, and Lithology Log for the Chia Gara Formation. (b, c, and d) Mud gas diagnostic ratio log for the Chia Gara Formation. The diagnostic ratios defined by Haworth et al. (1985), C_1/C_2, C_1/C_3 and C_1/nC_4 Vs Depth, WHR (wetness ratio), BHR (Balance ratio) and CHR (character ratio).

Conclusion

The hydrocarbon evaluation of the Cretaceous succession in the Bijeel-7 Well indicates significant variability in hydrocarbon phases across the formations, driven by depth and associated geochemical characteristics. The Shiranish Formation contains both residual oil and oil phases, with a transition from residual oil dominance in shallower intervals to oil dominance at greater depths. The Aqra and Bekhme formations exhibit similar mixed-phase behavior, though the Bekhme Formation also includes Residual and gas/oil phases at specific depths, highlighting its complexity. The Qamchuqa Formation is primarily residual oil-dominated, except for a distinct oil interval near its lower boundary. The Sarmord and Chia Gara formations display a consistent mix of residual oil and oil phases, with deeper intervals favoring oil dominance. These findings emphasize the potential of the studied formations for hydrocarbon exploration and development, with key insights into their phase transitions and depth-dependent variability.

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